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COUPLING OF WAVE AND CIRCULATION NUMERICAL MODELS AT GRAYS HARBOR ENTRANCE, WASHINGTON, USA

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Abstract: The interaction of waves and currents at an inlet entrance can be significant. Traditionally, numerical modelers have separated the processes of tidal circulation and wave transformation, but the surf zone and inlet are areas where the interactions are strong and should be numerically simulated to capture the resulting hydrodynamics. This paper describes performance of coupled wave and circulation models for both an idealized inlet setting and an application for Grays Harbor, Washington, concentrating on the influence of waves on currents. A comparison of tidal current simulations to tidal-plus-wave-induced current simulations shows that the interactions create gyres, longshore currents, rip currents, and "shadow zones" of relatively weak currents. It is concluded that accurate simulation of the hydrodynamics at coastal inlets requires coupling of wave and circulation models.

INTRODUCTION

Grays Harbor, located on the coast of southwest Washington, is one of the largest estuaries in the continental United States and has a correspondingly large tidal prism (Fig. 1). The entrance to Grays Harbor also experiences extreme Pacific Northwest waves. The U.S. Army Corps of Engineers (USACE) has built and maintained two rubble-mound jetties, a deep-draft navigation channel, and other navigational features in Grays Harbor. The North Jetty functions to block southward transport of sediment and to protect and maintain an entrance navigation channel; however, its effectiveness has decreased as a result of subsidence and deterioration. Recently, the north beach (Ocean Shores) has exhibited a tendency to erode, reversing a historic trend of advancement. Issues of concern

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14. ABSTRACT

The interaction of waves and currents at an inlet entrance can be significant. Traditionally, numerical modelers have separated the processes of tidal circulation and wave transformation, but the surf zone and inlet are areas where the interactions are strong and should be numerically simulated to capture the resulting hydrodynamics. This paper describes performance of coupled wave and circulation models for both an idealized inlet setting and an application for Grays Harbor, Washington, concentrating on the influence of waves on currents. A comparison of tidal current simulations to tidal-pluswave-induced current simulations shows that the interactions create gyres longshore currents, rip currents, and "shadow zones" of relatively weak currents. It is concluded that accurate simulation of the hydrodynamics at coastal inlets requires coupling of wave and circulation models.

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include future channel maintenance requirements, jetty maintenance if the North Beach recedes, and the sediment supply to Damon Point from the bypassed sediment.

As part of the USACE navigation study at Grays Harbor, field data were collected in 1999 and 2001 (Osborne et al. 2002). These measurements, together with physical and numerical models, are being analyzed to understand this large tidal inlet entrance, assess the functionality of the North Jetty, and determine sediment transport mechanisms in this high-energy environment (Cialone and Kraus 2001, 2002).

This paper describes the coupling of a wave model and a circulation model to examine tidal currents, wave-induced currents, and wave transformation and their interactions in the Ocean Shores region, at the North Jetty tip, and in the inlet entrance. Of particular interest are the formation and location of rip currents induced by radiation stress gradients in the forcing of the circulation model. Processes are also examined for the situation of an idealized coastal inlet.

FIELD DATA COLLECTION

Field data were collected in 1999 at seven locations extending from seaward of Grays Harbor and through the entrance to record surface wave propagation and currents (Fig. 1). These measurements capture tidal flow and change of water level by tide and wind, as well as wave propagation into the bay, that transport sediment into the navigation channel and over oyster-ground leasing areas. In 2001, measurements of nearshore currents at Ocean Shores and waves and currents near the north jetty tip were also made. The 1999 data-collection program included waves, water level, tidal current through the water column, and suspended sediment at seven bottom-residing tripods for a 2-month period. The tripods were deployed along or near the navigation channel, extending from the entrance, through the inlet, and into the bay. The year 2001 data-collection program included similar measurements at the North Jetty for a 1-month period and two short–term (3-5 day) deployments in the nearshore zone at Ocean Shores (Osborne et al. 2002).

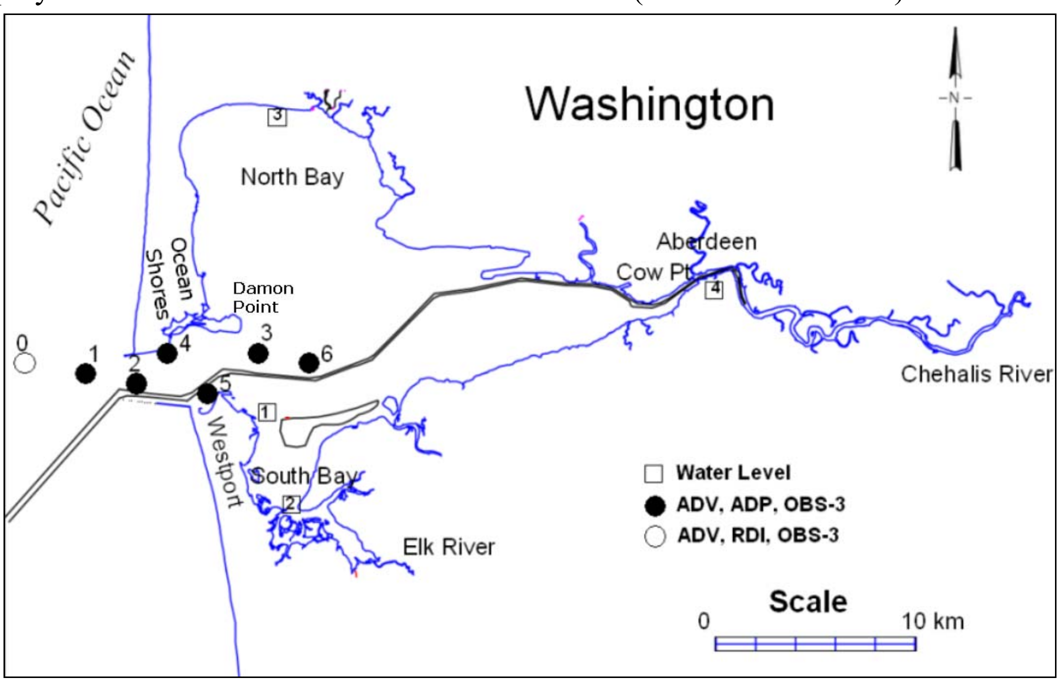

Fig. 1. Study area map and instrument locations for 1999 deployment

NUMERICAL SIMULATIONS

Validation

Wave and circulation numerical models were applied to the Grays Harbor, Washington, region as part of the USACE navigation study. Computational grids were developed for the tidal circulation model ADvanced CIRCulation (ADCIRC) (Luettich et al. 1992) and the spectral wave model STeady-state spectral WAVE (STWAVE) (Smith et al. 2001). Bathymetry for the computational grids represented conditions in 1999 (the field data collection time period). The wave model validation described in Cialone and Kraus (2001) showed good agreement between measured and modeled wave transformation through the inlet entrance for the 1999 field data collection time period (month 1), but it was noted that dynamically linking the wave and current models to include the transformation of waves by currents and water level could improve results. Validation of the circulation model for the first month of the 1999 field data collection time period also shows tidal elevations compare well with measurements around the periphery of the bay at Stations 1 through 4 (Table 1), with the maximum error being 5.8 percent.

Comparison of calculated currents with measured also indicates good agreement at Velocity Stations 2 through 6 (Table 2). This inlet throat area is clearly tide-dominated, and such results can be expected. Station 1, however, shows poor agreement. Wave-induced currents in this region are significant, hence improved calculation requires dynamic linking of the wave and circulation models. In this paper, the influence of waves on currents is examined by means of a coupled model approach.

Table 1. Wave Model Validation for Tide Stations 1 through 4

Station	E_{rms}, m	Mean Error, m	Range, m	Percent Error, %
Tide 1	0.12	0.05	3.32	3.5
Tide 2	0.13	0.05	3.39	3.9
Tide 3	0.17	0.04	2.93	5.8
Tide 4	0.13	0.00	3.78	3.4

Table 2. Current Model Validation for Velocity Stations 1 through 6

Station	E_{rms}, cm/sec	Mean Error, cm/sec	Range, cm/sec	Percent Error, %
Velocity 1	28.4	23.8	149	19.1
Velocity 2	11.0	3.3	137	8.0
Velocity 3	11.3	4.5	131	8.6
Velocity 4	12.1	1.9	165	7.3
Velocity 5	10.7	-0.3	124	8.7
Velocity 6	12.0	-5.3	126	9.6

Model Coupling

The Grays Harbor data set provides an opportunity to rigorously examine representation of the wave-current interaction through the wave-action equation, current-induced breaking wave blocking by a current, and diffraction. Coupling of the two models requires exchange of the wave radiation stresses and currents in an iterative approach. This coupling is accomplished in the Surface-water Modeling System (SMS) Steering Module (Zundel et al. 2002a, Zundel, et al. 2002b). The SMS is a pre- and post-processor developed for operating various numerical hydrodynamic models (Militello and Zundel 1999). The SMS Steering Module was developed to automate repetitive user tasks and facilitate data sharing between circulation and wave propagation numerical models. At present, the Steering Module couples the finite-element circulation model ADCIRC and the finite-difference wave model STWAVE or the finite-difference circulation model M2D (Militello 1998; Kraus and Militello 1999; Militello and Zundel 2003) and the STWAVE model. Future work will allow other USACE circulation and wave models to be coupled via the Steering Module, as well as coupling to sediment transport and morphology change models.

Idealized Inlet Simulations

Initially, simulations with a plane beach test basin were made to assess the performance of the coupled models. The idealized inlet and bay had a constant depth of 10 m, and the offshore sloped to a 40-m depth. Idealized inlet configurations examined in the initial phase of the coupled model study then progressed to include 1) an equilibrium beach profile extending to a depth of 30 m with a 5-m deep inlet and bay, and 2) an equilibrium beach profile with an idealized (circular) ebb shoal (Fig. 2). This configuration was selected to represent, in an idealized way, conditions at Shinnecock Inlet, NY (Militello and Kraus 2000). Results from the equilibrium profile with ebb shoal configuration are presented and discussed herein.

The ADCIRC domain extended 25 km in the longshore direction and 10 km from the bay to the offshore (ocean) boundary (Fig. 3). The STWAVE domain was a subset of the ADCIRC domain, extending 15 km in the alongshore direction and 8 km in the on-offshore direction. Wave model simulations included normal and obliquely incident waves with

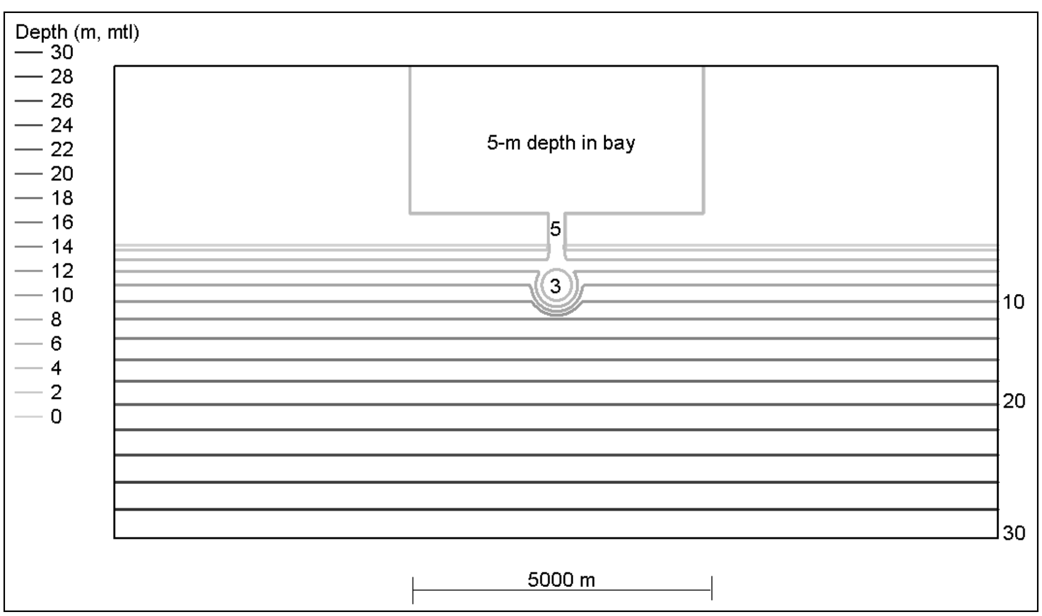

Fig. 2. Idealized inlet bathymetry to approximate conditions at Shinnecock Inlet, NY

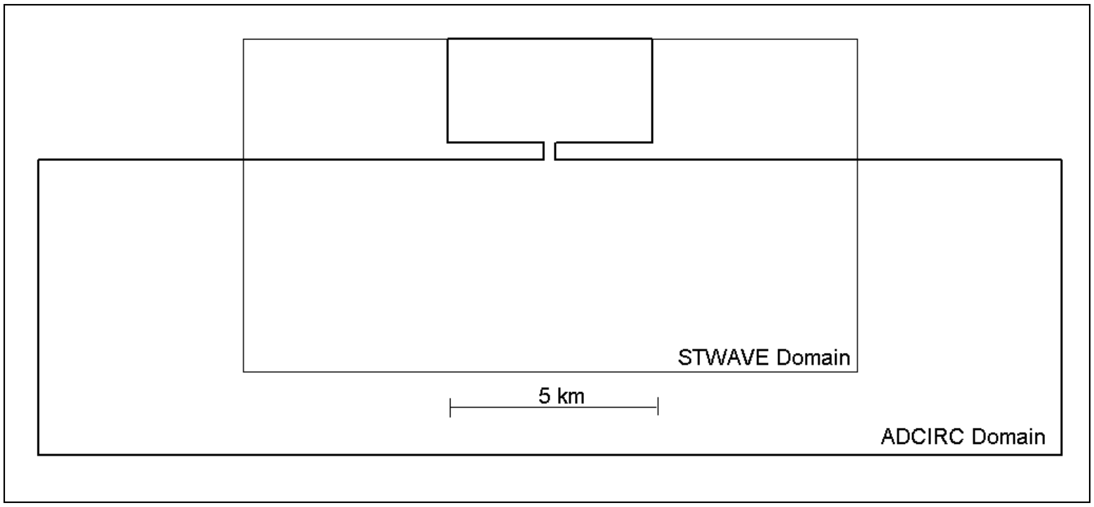

Fig. 3. ADCIRC and STWAVE domains for idealized inlet model simulations

and without the influence of tidal currents to examine modification of waves by currents. Discussion focuses on the current generated for the largest modeled storm waves (4 m, 12 sec). Normal and obliquely incident waves are considered in the discussion. The ocean boundary of the circulation model was forced with a sinusoidal time series to represent a tide with a 1.5-m range and 12.42-hr period. The model simulation period was 1 day. The wave model simulations were made every 3 hr, and radiation stress gradients were spatially interpolated from the STWAVE domain to the ADCIRC domain. Beyond the wave model domain, radiation stress gradients were extrapolated to zero using a standard sigmoidal function. Radiation stress gradients were then temporally interpolated for every ADCIRC timestep.

Figs. 4a and 5a show circulation model results at peak flood and peak ebb, respectively, with no wave coupling (tidal currents only). Flood currents increase on approach to the inlet throat (constriction), reaching a maximum speed of about 0.8 m/sec. Ebb currents behave similarly, with maximum currents speeds in the inlet throat (0.8 m/sec) and diminishing current speeds upon exiting the inlet.

Figs. 4b and 5b show calculated current patterns at peak flood and peak ebb, respectively, with the inclusion of wave-induced currents generated by 4-m, 12-sec normally incident waves. Fig. 4b shows strong (1.8 m/sec) currents on the ebb shoal caused by large gradients in radiation stress (breaking waves) in this region. Large gyres are observed on both sides of the ebb shoal location caused by lateral gradients in radiation stress (refraction) combined with the tidal currents. Currents in the inlet throat are strongest along the "side walls" of the inlet. Fig. 5b (ebb condition) also shows strong currents (1.5 m/sec) on the ebb shoal caused by breaking waves. In this case, the interaction of waves with an opposing current causes a strong (1.3 m/sec) longshore current to the left and right directions.

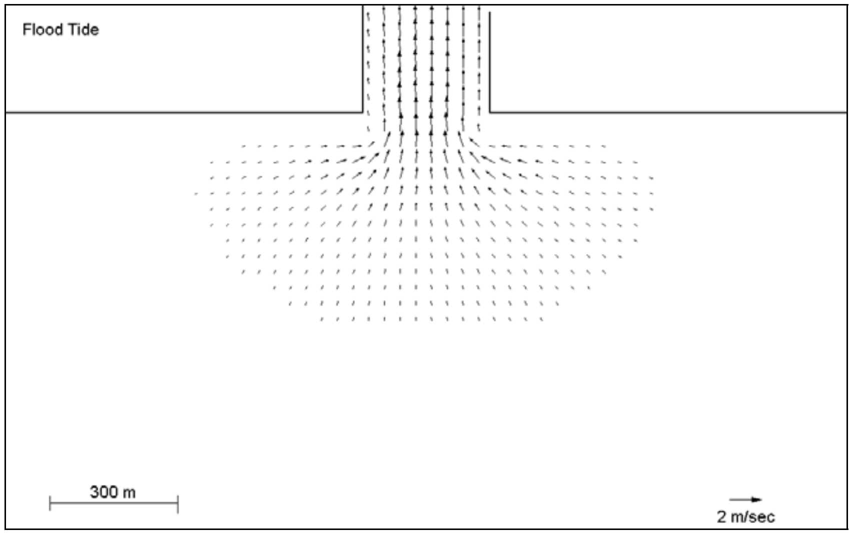

Fig. 4a. Idealized inlet flood tidal currents

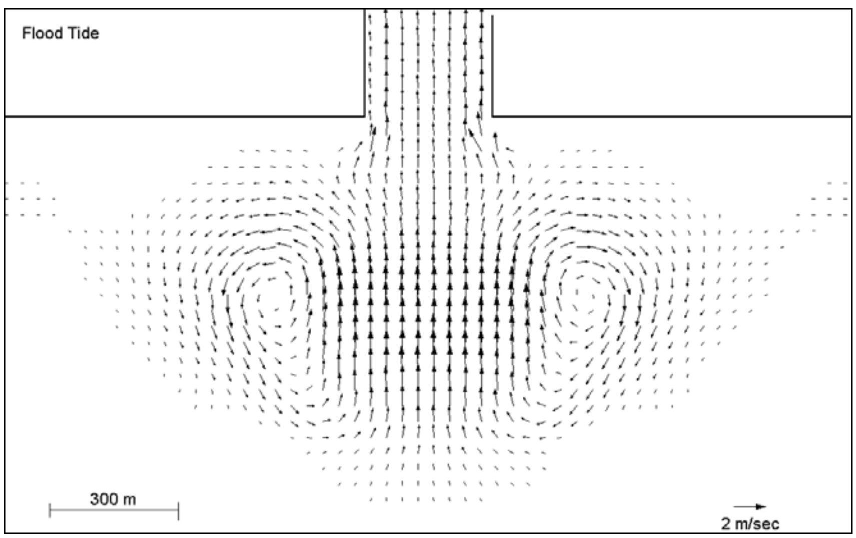

Fig. 4b. Idealized inlet flood tidal currents and normally-incident wave-induced currents

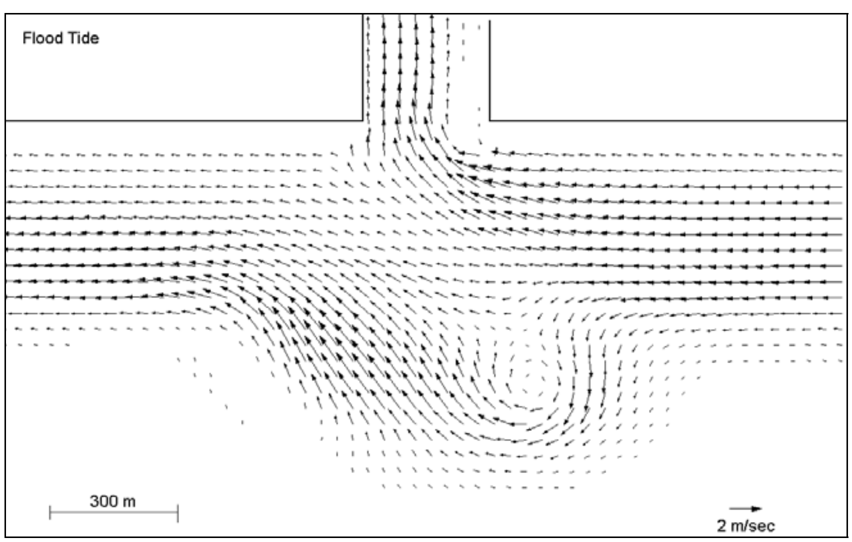

Fig. 4c. Idealized inlet flood tidal currents and obliquely-incident wave-induced currents

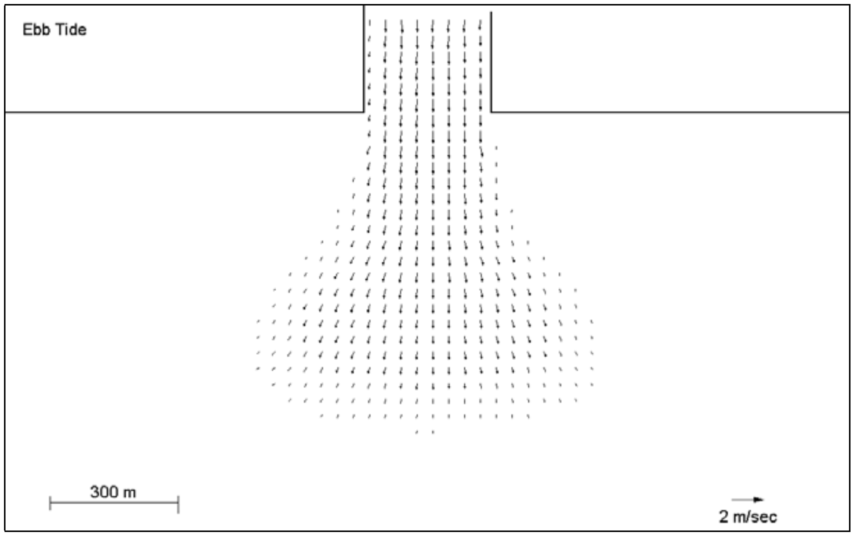

Fig. 5a. Idealized inlet ebb tidal currents

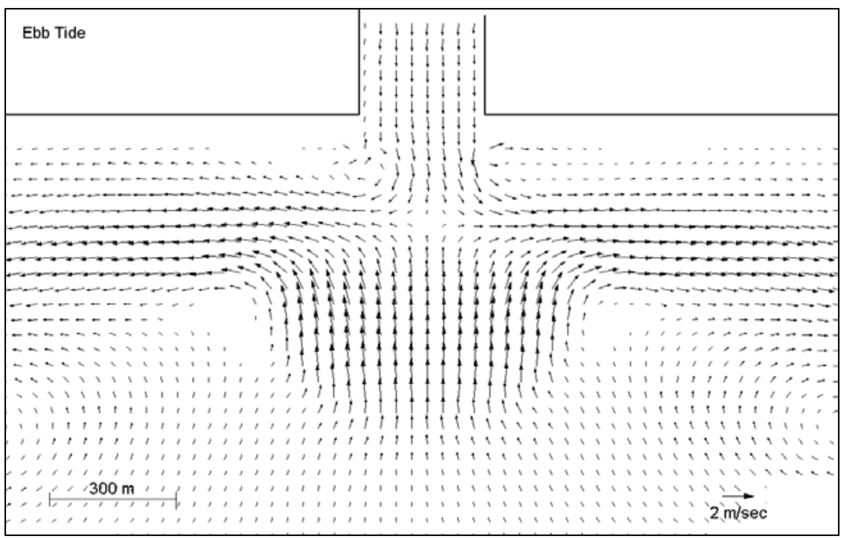

Fig. 5b. Idealized inlet ebb tidal currents and normally-incident wave-induced currents

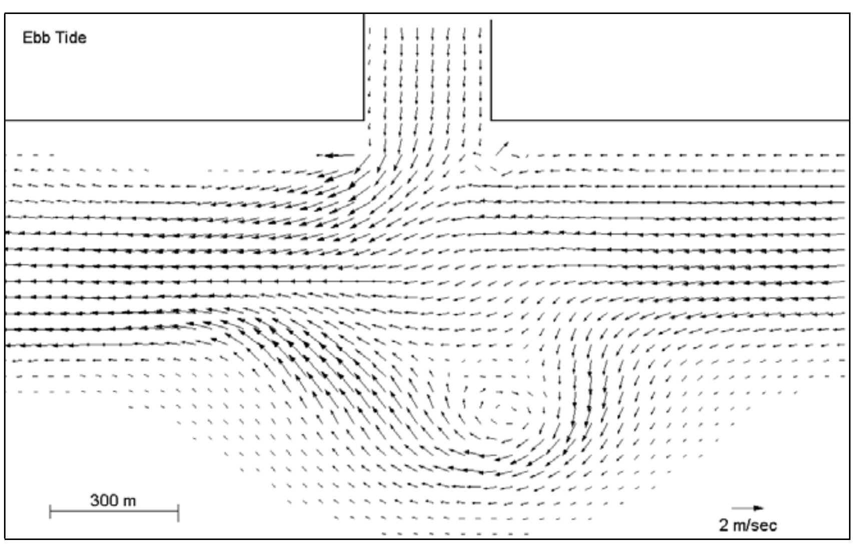

Fig. 5c. Idealized inlet ebb tidal currents and obliquely-incident wave-induced currents

Figs. 4c and 5c show circulation model results at peak flood and peak ebb, respectively, with the inclusion of wave-induced currents generated by 4-m, 12-sec obliquely-incident waves (waves from right, 30 deg from shore normal). Fig. 4 shows strong currents (1.8 m/sec) near the outer portion of the ebb shoal, a strong longshore current (1.3-1.5 m/sec) and strong currents on the left side of the inlet throat. The region of strong longshore currents represent a 500-m wide surf zone for this storm wave condition. In contrast, the tidal current (Fig. 4a) shows little or no longshore component. Breaking of obliquely incident waves is the driving mechanism of these longshore currents.

Fig. 5c shows the confluence of ebb tidal currents with wave-induced currents to the left of the ebb shoal, strengthening the longshore current to approximately 1.6-1.8 m/sec. Longshore currents on the right side of the inlet are approximately 1.3 m/sec. A lobe of weak (null) currents is observed near the left, downdrift shoreline and currents increase 500 m further downdrift. This weak current zone suggests a corresponding weak sediment transport zone and hence is a possible mechanism in the formation of a downdrift attachment point.

Grays Harbor, Washington, Simulations

From the idealized inlet model coupling simulations, the significance of wave-induced currents in the surf zone, wave-current interaction at the inlet entrance, surf zone resolution, and finite-difference and finite-element grid resolution compatibility were determined to be major factors in the coupling process. Coupling of the wave and circulation models for the Grays Harbor application therefore required addressing these considerations.

A finite difference mesh was developed for the Grays Harbor area (Fig. 6). Grid cells range from 50 km near the offshore boundary to 25 m in the surf zone. The fine nearshore resolution is required to accommodate the interpolation of radiation stress gradients from the finite difference wave model domain to the finite element circulation model domain (Fig. 7). Radiation stress gradients produced with the STWAVE model were transformed to the ADCIRC domain to examine tidal plus wave-induced currents. Beyond the wave model domain, radiation stress gradients were extrapolated to zero using a standard sigmoidal function. Currents from the finite-element circulation model were transformed from the finite-element model to the finite difference wave model to examine the influence of currents on waves. Two-way passing between models was also accomplished. This paper concentrates on the effect of waves on currents.

Results are presented for a 5-day ADCIRC simulation. The ADCIRC model was forced with a spring tide and a) no waves, b) 5-m 13-sec west-northwest (WNW) wave, and c) 6-m, 14-sec west-southwest (WSW) waves. Ideally, radiation stress gradients would be passed to the circulation model every 1-3 hr during the simulation to include variation in water level on wave transformation through a tidal cycle. However, these single-wave condition simulations coupled the models at the start, mid-simulation, and end to reduce simulation time and simplify the analysis process. Radiation stress gradients from the three STWAVE simulations were then temporally interpolated for every ADCIRC timestep.

Figs. 8 and 9 show flood and ebb tidal currents and wave-induced currents for WNW and WSW waves. As in the idealized case, the flood tidal currents increase on approach to

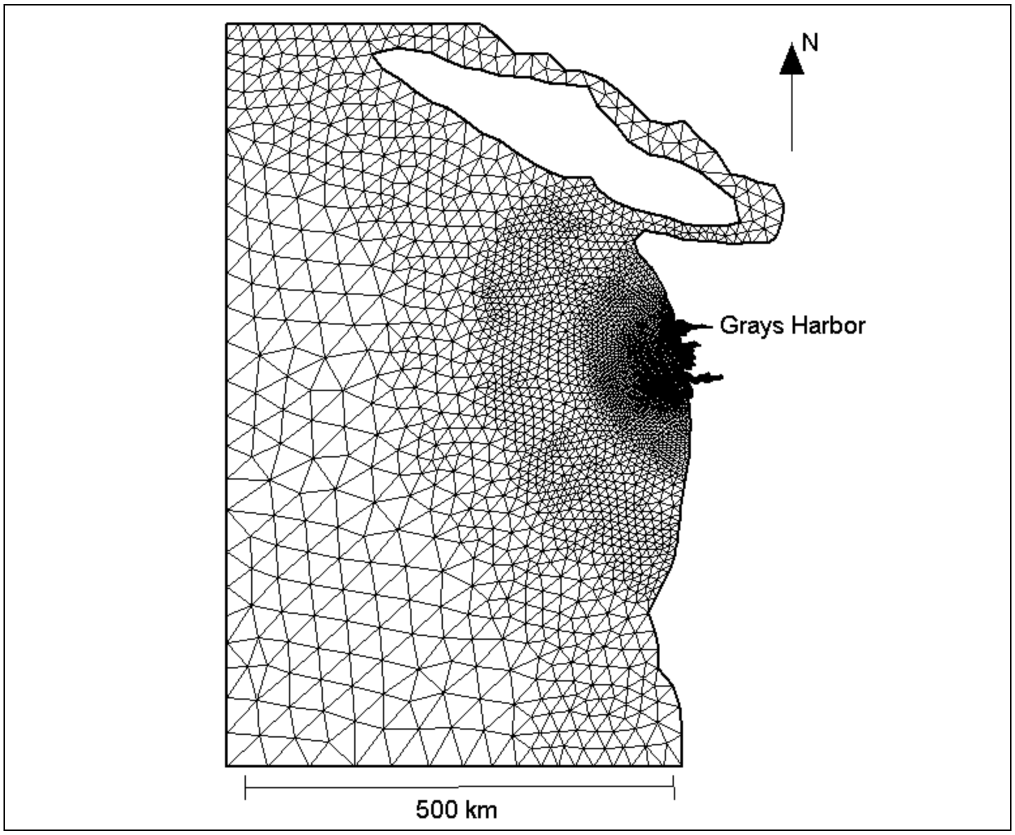

Fig. 6. ADCIRC finite-difference mesh for Grays Harbor, Washington, application

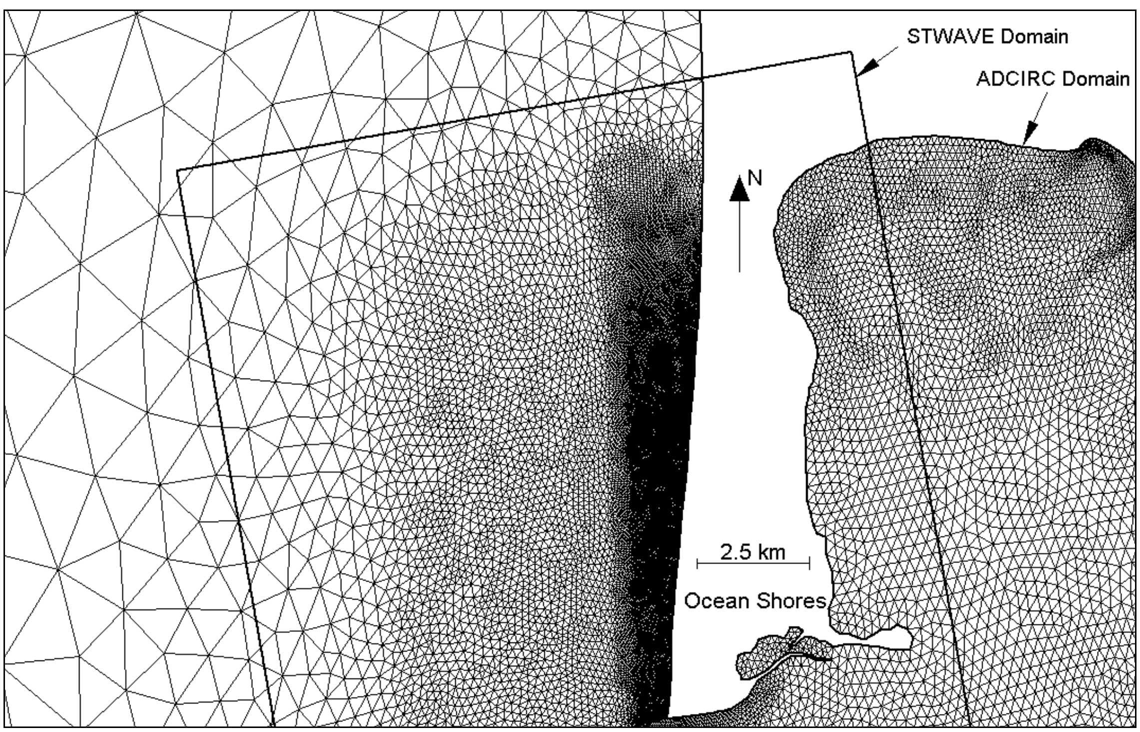

Fig. 7. ADCIRC mesh for Grays Harbor: fine resolution in the surf zone mesh and a portion of the STWAVE grid boundary

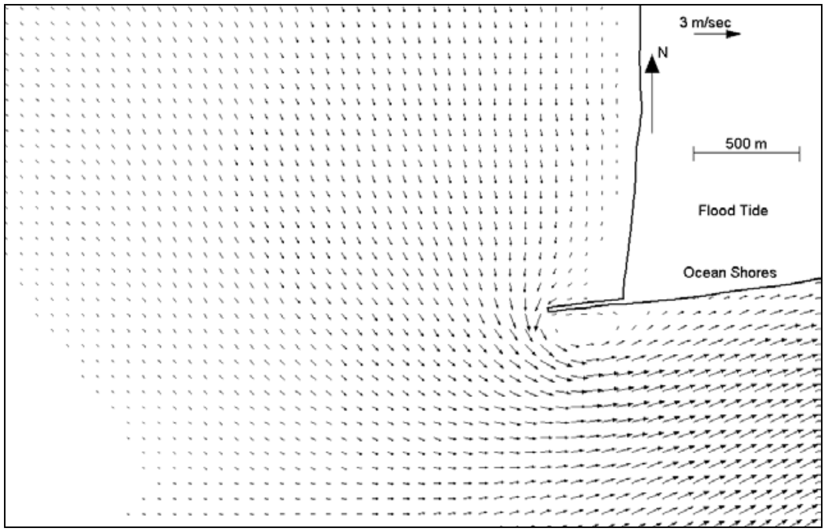

Fig. 8a. Grays Harbor entrance flood tidal currents

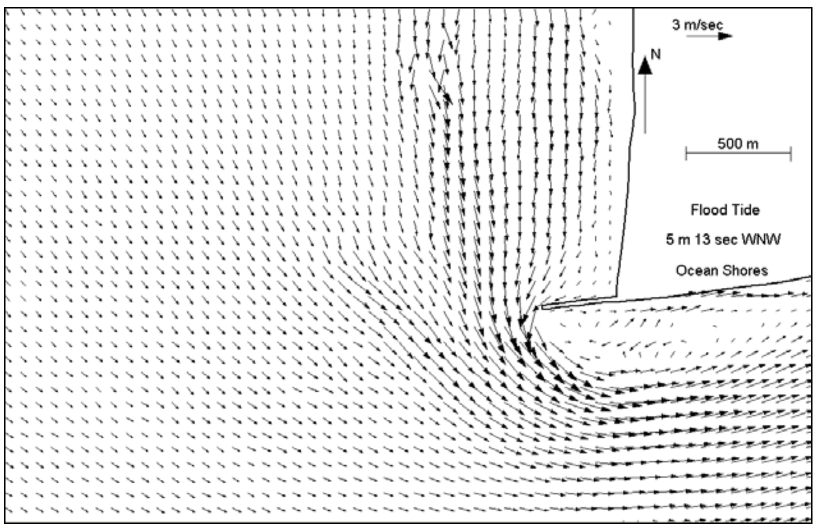

Fig. 8b. Grays Harbor entrance flood tidal currents and WNW wave-induced currents

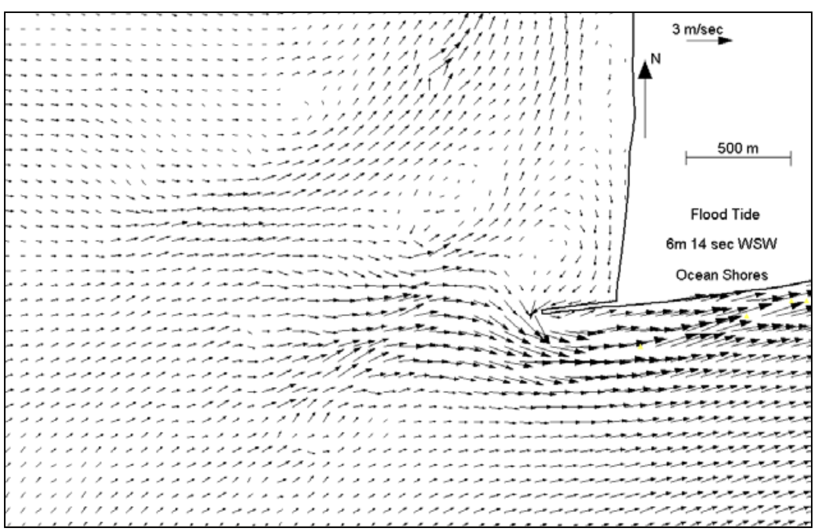

Fig. 8c. Grays Harbor entrance flood tidal currents and WSW wave-induced currents

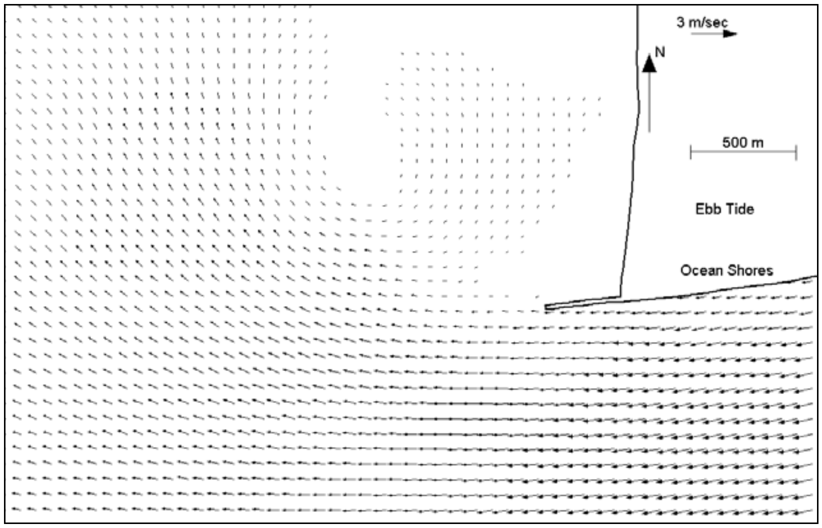

Fig. 9a. Grays Harbor entrance ebb tidal current

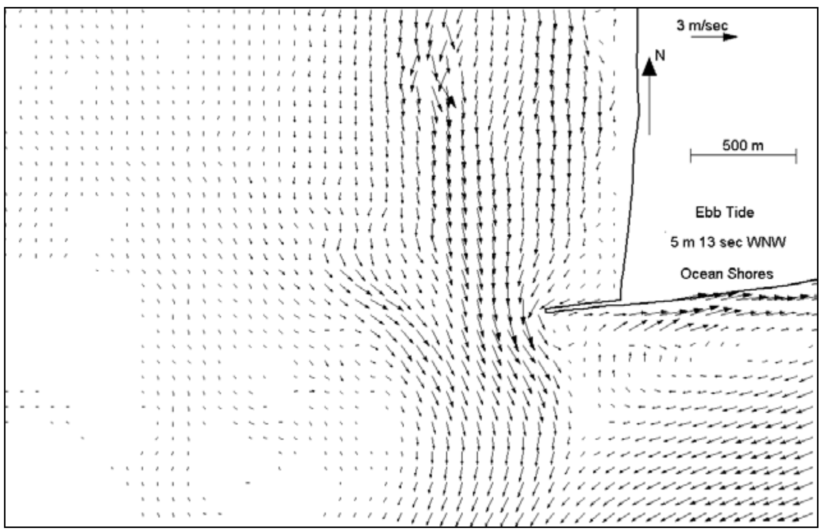

Fig. 9b. Grays Harbor entrance ebb tidal currents and WNW wave-induced currents

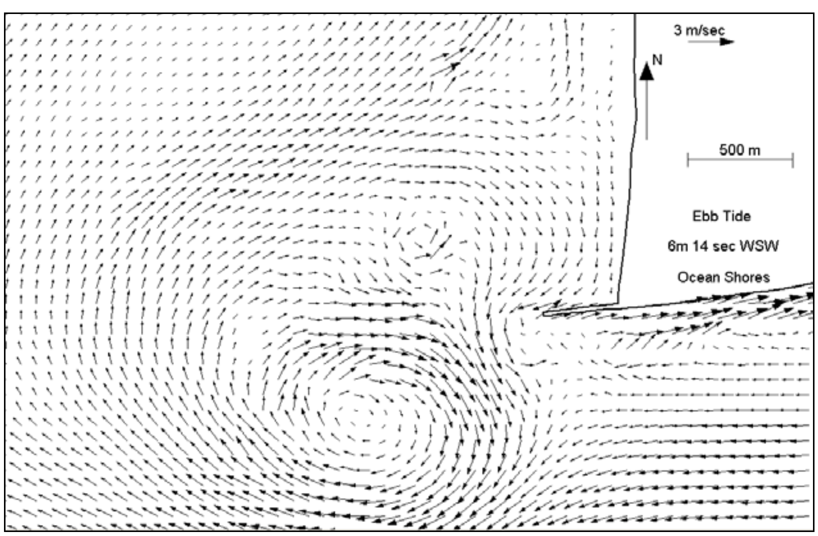

Fig. 9c. Grays Harbor entrance ebb tidal currents and WSW wave-induced currents

the inlet throat (constriction) (Fig. 8a). Maximum currents are approximately 1.3 m/sec. The longshore current is approximately 0.4 m/sec, and the current near the north jetty tip is approximately 0.9 m/sec. With inclusion of waves from the WNW, the flood tidal currents are reinforced on the north side of the inlet, and the longshore current increases to 1.6 m/sec (Fig. 8b). Currents near the jetty tip increase significantly with the inclusion of wave-induced currents (from 0.9 to 2.6 m/sec). In Fig. 8c, the confluence of flood tide and WSW wave-induced currents are strengthened along the south side of the north jetty (2.8 m/sec). Two bands of northward-directed flow are controlled by bathymetric features, and a flow reversal (southward current) is observed for approximately 500 m north of the north jetty. A clockwise gyre is also present in this region.

Fig. 9a shows ebb tidal currents are strong in the inlet throat and then diminish upon exiting the flow constriction. Maximum currents are approximately 1.5 m/sec in the inlet throat and the longshore current is approximately 0.2 m/sec. Fig. 9b shows that the confluence of the ebb current and the north-to-south wave-induced current creates a southbound current across the inlet throat. The ebb jet is deflected and re-directed to the south. The longshore current is approximately 1.4-1.5 m/sec. Currents on the south side of the north jetty are approximately 2 m/sec and oppose the ebb flow. Waves from the WSW create a northward longshore current (1.3 m/sec) that intersects with the ebb jet to create a large gyre in the inlet (Fig. 9c). Currents in the gyre approach 2 m/sec. Again, a flow reversal (southward current) is observed for approximately 500 m north of the north jetty. Currents on the south side of the north jetty are approximately 2.6 m/sec and oppose the ebb flow.

CONCLUSIONS

Coupling of wave and circulation models for both an idealized inlet setting and an application for Grays Harbor, Washington, concentrating on the influence of waves on currents, has been presented. This coupling technology is necessary to represent strong interactions between waves and currents in the surf zone and inlet. Comparison of tidal current simulations to tidal-plus-wave-induced current simulations shows that the interactions create gyres, longshore currents, rip currents, and "shadow zones" of relatively weak currents.

Model coupling for an idealized inlet gives physical insights into such processes as determining areas where interactions are most significant and inlet flood and ebb dominance zones. Coupling also provides calculation insights for improving representation of the phenomena, such as how to transition between non-coincident model boundaries, cell resolution in strong wave-current interaction areas, and cell size compatibility between finite difference and finite element models.

Model coupling for the Grays Harbor, Washington, numerical study illustrates complexities of any real-world application such as additional bathymetric features, structures, shoreline offset, and non-uniform grid resolution. The Steering Module successfully demonstrated that coupling of wave and circulation models in this complex environment is both attainable and necessary to capture the interactions that occur in nature.

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